

THIRD SEMIANNUAL REPORT

NASA Grant NGR- 05-009-030

Physical Processes in the
Magneto-Plasmadynamic Arc

NOVEMBER 1967

GPO PRICE \$ _____
CFSTI PRICE(S) \$ _____
Hard copy (HC) \$ 2.00
Microfiche (MF) _____

ff 653 July 85

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FACILITY FORM 502	N68 - 13516 (ACCESSION NUMBER)	_____ (THRU)
	<u>22</u> (PAGES)	_____ (CODE)
	<u>CR-91529</u> (NASA CR OR TMX OR AD NUMBER)	<u>25</u> (CATEGORY)

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Introduction

This report summarizes progress on NASA Grant NGR-05-009-030 during the third semiannual period March 1967 - September 1967.

The major effort during this period was devoted to a detailed investigation of the current spoke that was detected last year. Small Rogowski coils have been developed which have made it possible to map the current distribution and thus define the spoke structure more clearly.

Plasma flow velocities have been detected in the spoke with biased electric probes. The plasma appears to rotate with the spoke and exhibits a complex internal structure.

1. Operating conditions

Nearly all of the work during this period has been performed under the following standard conditions:

Arc voltage: 75 volts

Arc current: 550 amps

B_{z0} : 2200 gauss

Propellant: Argon

The propellant flow rate is estimated by combining our prior knowledge of the total content of the gas plenum chamber with the flow duration as observed with a fast ion gauge placed at the accelerator muzzle. This rate is about .02 g/sec.

Measurements made with the fast ion gauge indicate that the neutral gas density in the arc region is about 5×10^{14} atoms/cm³. Furthermore, the gas flow seems to be azimuthally symmetric in this region.

The rotation frequency of the current spoke under standard conditions is approximately 40 kc. The variation of rotation frequency with the product of arc current and magnetic field strength is shown in Figure 1.

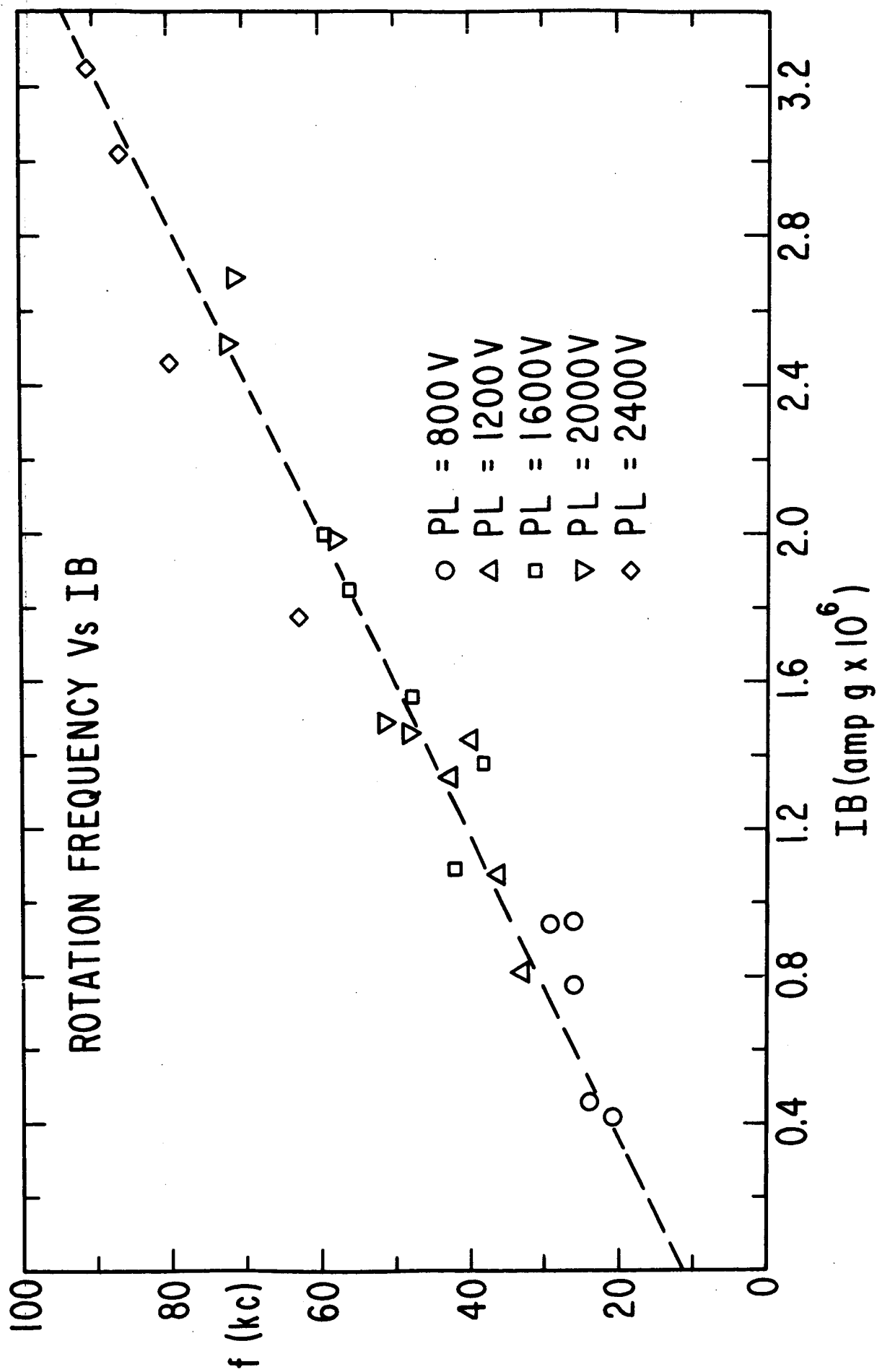


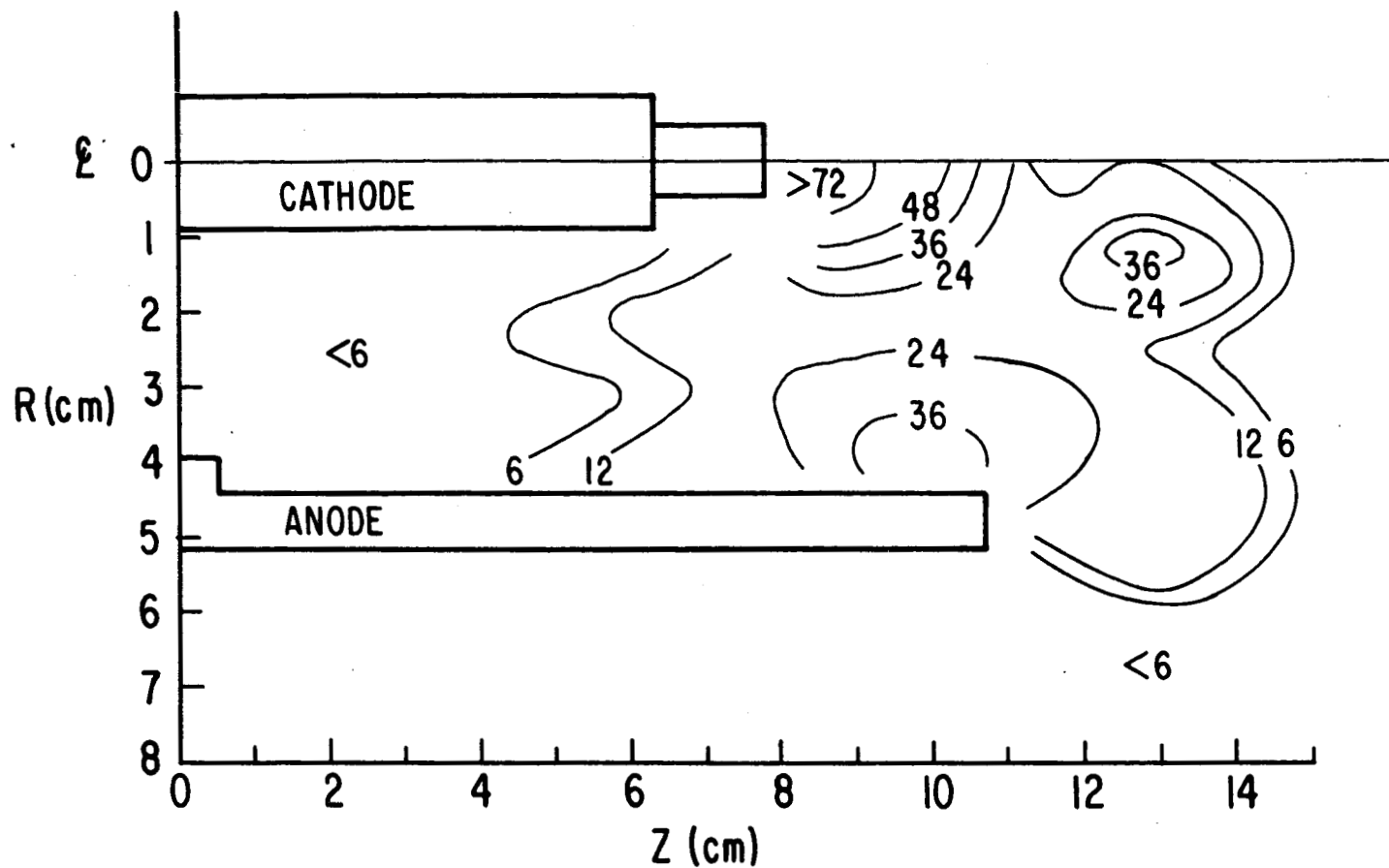
Fig. 1. Spoke rotation frequency vs. IB.

2. Spatial distribution of current

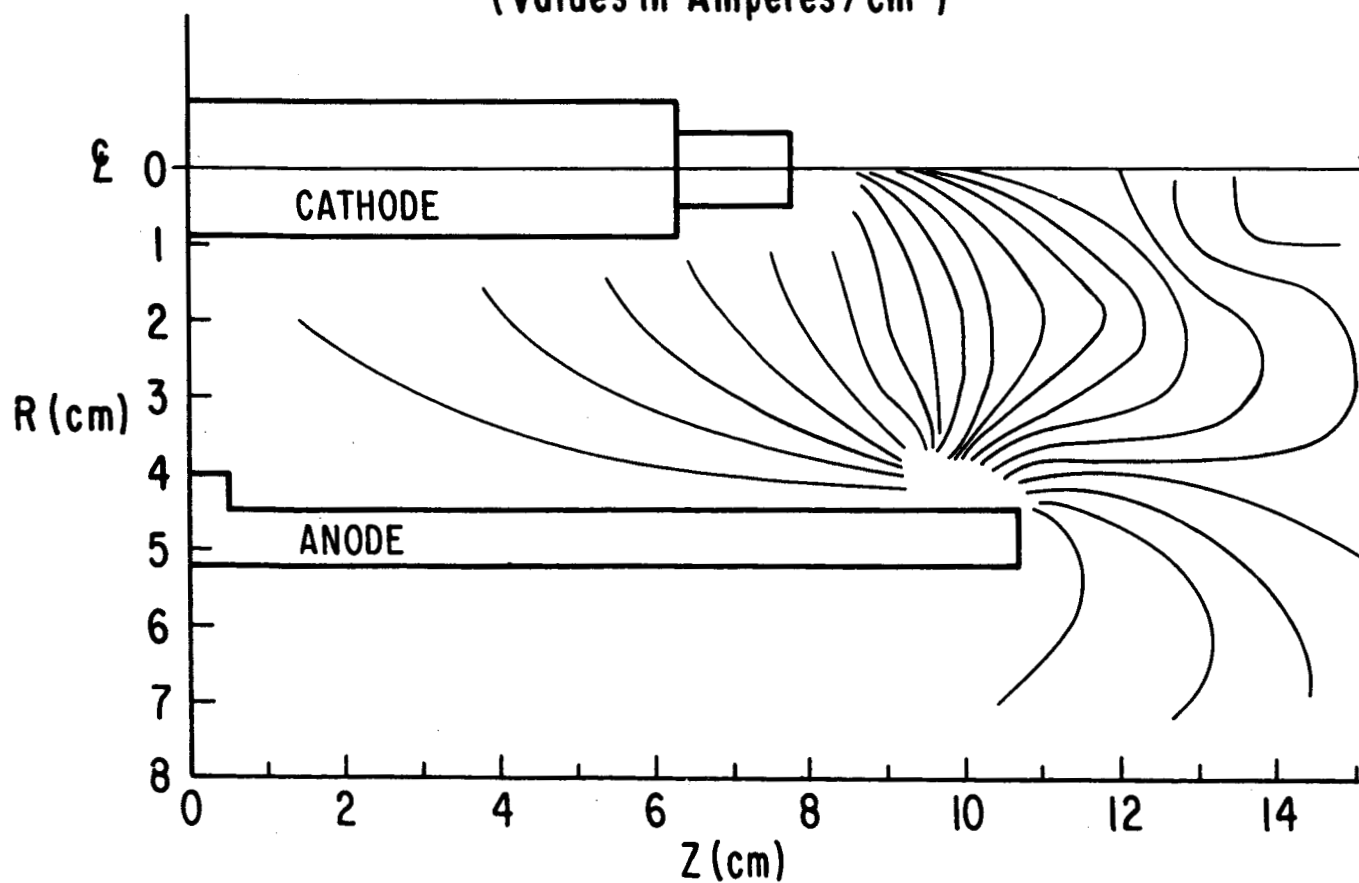
An improved, more compact Rogowski coil design has been employed for detailed measurements of the current distribution. Two coils, each having a collection area of 1.8 cm^2 , were used to measure the components of \vec{J} in the arc region. A matrix of points in the r - z plane was covered, the r interval being 0.5 cm. and the z interval 1.0 cm. The combined data was then used to determine the magnitude and direction of the current density vector at each point. The resulting current streamlines and current density contours are shown in Figure 2.

The azimuthal distribution of radial current is shown in Figure 3. These points are taken from a J_r run along a radius at $z = 9.5 \text{ cm.}$, which is approximately the axial location of the maximum current density. The pair of points plotted at each radius represent the half-intensity levels of the current pulse as seen on the Rogowski coil output. The error bars are derived from the scatter among the several traces on the multi-rotation overlay. It can be seen that the scatter associated with the rise of the current is far less than that which accompanies the drop; such behavior is commonly observed in "current sheet" plasma accelerators. It is clear that there is no significant spiralling of the current in the body of the arc; thus no azimuthal current flows in this region.

The existence of a significant potential drop in the anode sheath and the corresponding large radial electric field in that region leads one to conclude that the electrons in the anode sheath should experience an ExB drift in the θ direction. This would constitute an azimuthal current flow which should be detectable via the magnetic field it produces. Figure 4 shows the integrated output of an axial magnetic field probe positioned just outside of the accelerator muzzle and at a radius slightly less than that of the anode sheath. The base line of the picture is the magnitude



Current Density Magnitude at Center of Fin
(Values in Amperes / cm^2)



Current Streamlines at Center of Fin

Fig. 2. Equal current density contours and current streamlines at center of spoke.

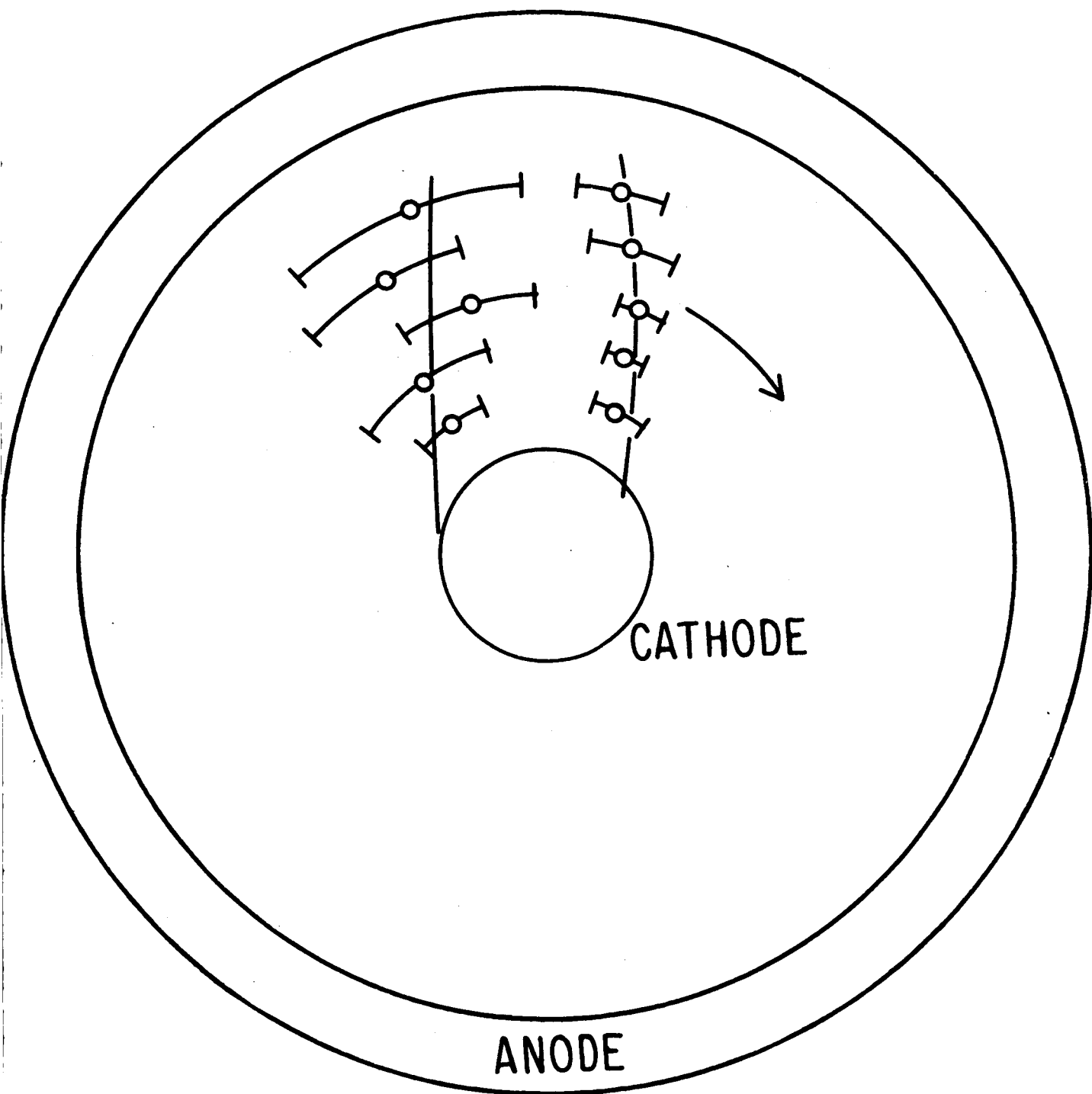


Fig. 3. \ominus Distribution of current

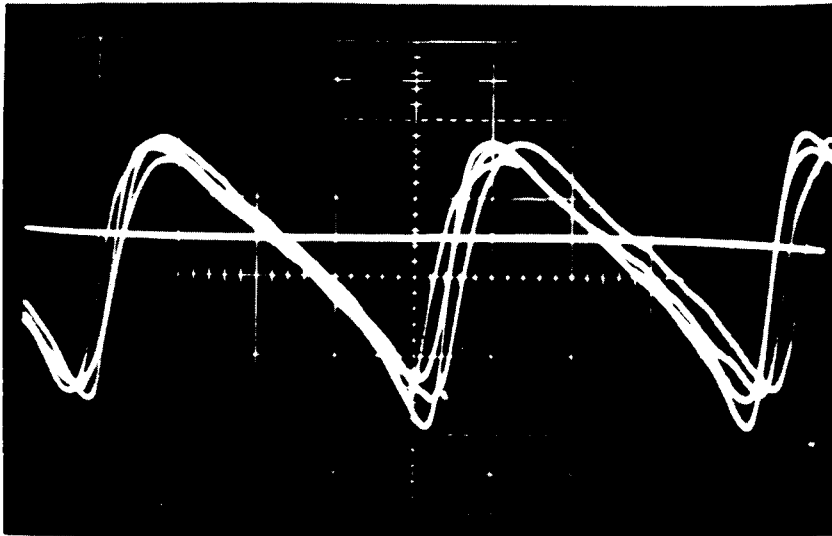


Fig. 4. ΔB_z at a radius slightly less than that of the anode sheath. Sweep 5 $\mu\text{sec./cm.}$

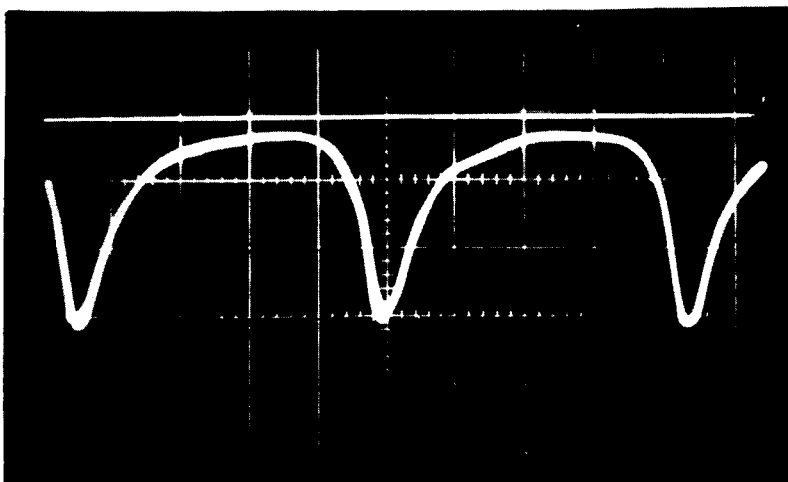


Fig. 5. Photomultiplier telescope output. Sweep 5 $\mu\text{sec./cm.}$

of the bias field with no arc present. A pure radial spoke with no azimuthal current in the anode sheath would produce a symmetric perturbation about the vacuum magnetic field. The fact that the observed perturbation is not symmetric therefore indicates that an azimuthal current flows in the anode sheath. The magnitude of the asymmetry corresponds to a total azimuthal current of the order of 50 amps.

3. Optical observations

A photomultiplier telescope with a very limited acceptance angle has been developed. With this instrument it is possible to measure spatial variations in the intensity of the total visible radiation from the arc. Figure 5 is a typical scope display of the photomultiplier output at one point in space. The maximum light intensity seems to be well correlated with the maximum current density in the arc. The intensity of the light radiated from the spoke is much greater than that from any other region of the accelerator except for the incandescent cathode. The magnitude of the maximum intensity seems to be independent of radial position along the spoke.

The output of the photomultiplier telescope is now being utilized as a very reliable phase reference trigger to overlay data traces for successive spoke rotations. Its performance in this application indicates that such a device would be useful as a "spoke detector" in steady state MPD arcs, where internal diagnostics are not practical.

A similar telescope has been mounted on the input of a spectrograph to permit observation of the spatial variations of line intensities.

The electron temperature is being determined from line intensity ratios of radiation from AI, AII and H (1% doping). Initial observations of intensity ratios of atomic lines indicate that the electron temperature

is of the order of 1 eV. In this temperature range, however, the ratio of atomic line intensities is relatively insensitive to the electron temperature. The sensitivity will be increased by using ratios of ionic line intensities, since there are a few AII lines which have excitation energies differing by approximately 3 eV.

4. Electric fields

The electric fields in the arc region have been measured using differential floating double probes. The reproducibility of electric field measurements in the spoke is fairly good at larger radii where the spoke structure is well defined. Near the axis much scatter exists in the data, probably due to slight variations in the shape of the spoke in this region as it rotates.

Figure 6 shows values of the radial and azimuthal electric field components measured in the current spoke.

5. Spatial potential distribution

Through better probe design and a more reliable phase reference from the photomultiplier telescope, it has been possible to improve the equipotential data included in the last report. This improved data is shown in Figure 7. The potential map is plotted with the center of the spoke in the top half of the plane. The presence of a thin anode sheath with approximately a 30 volt potential drop is clearly evident.

The radial dependence of the floating potential in the current spoke is shown in Figure 8. The radial electric field deduced from the slope of the floating potential plot agrees, within scatter, with that measured directly with the differential probes.

The variation of the potential drop in the anode sheath with changes

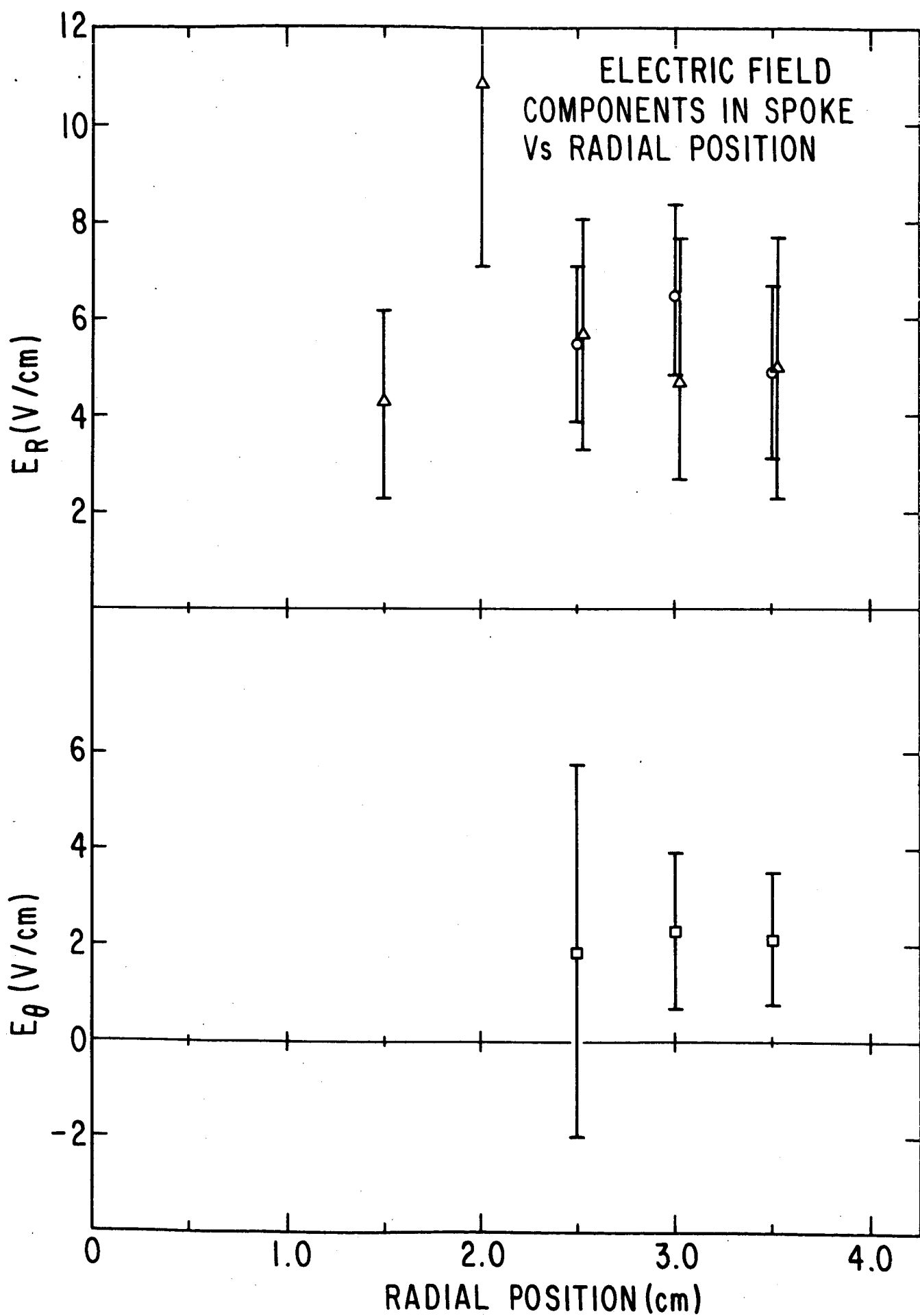


Fig. 6. Radial and azimuthal electric fields in the spoke.

RUN KI6S

CATHODE REF.

PL 1200 V

BF 900 V

$V_A - V_K \approx 70V$

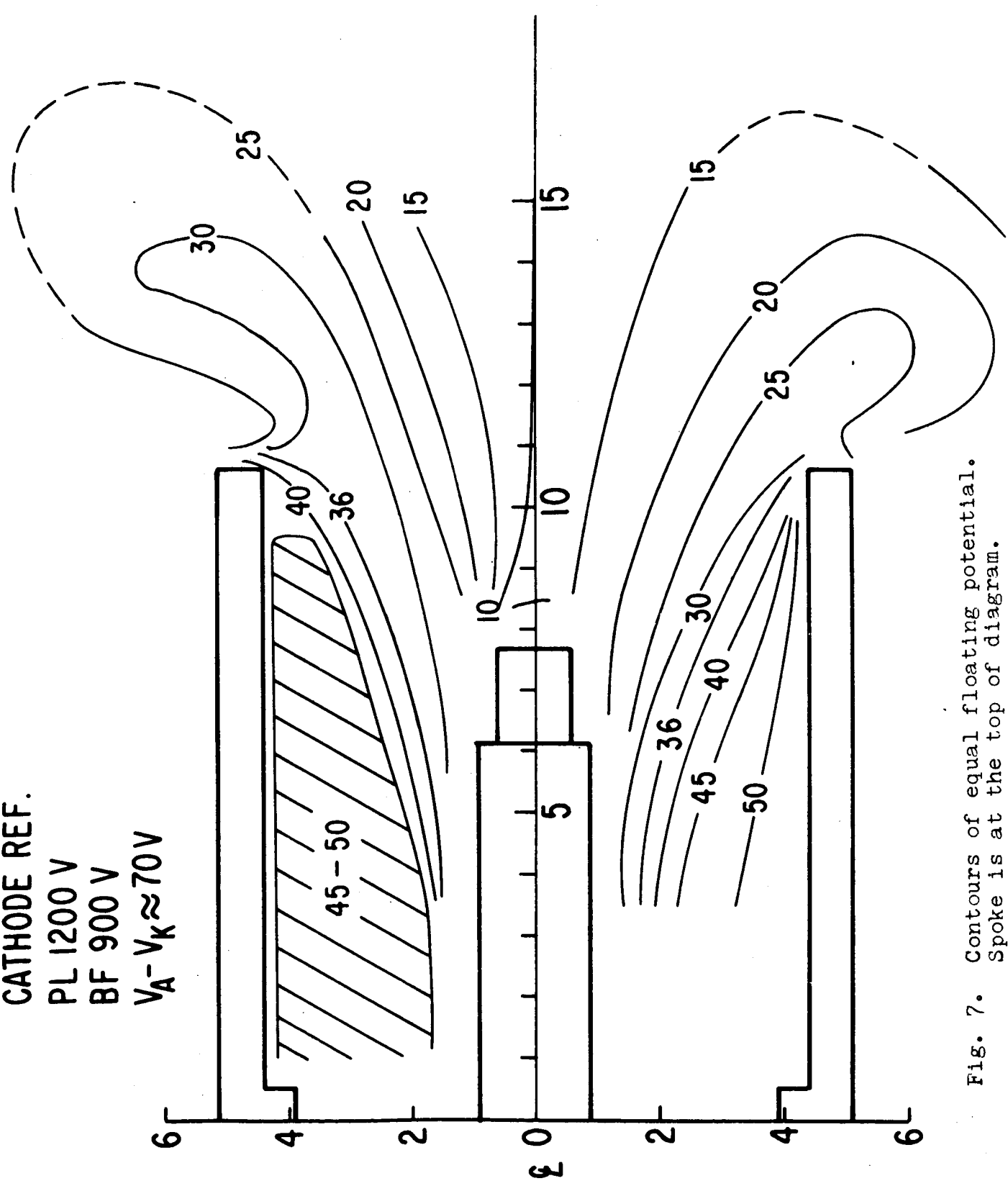


Fig. 7. Contours of equal floating potential. Spike is at the top of diagram.

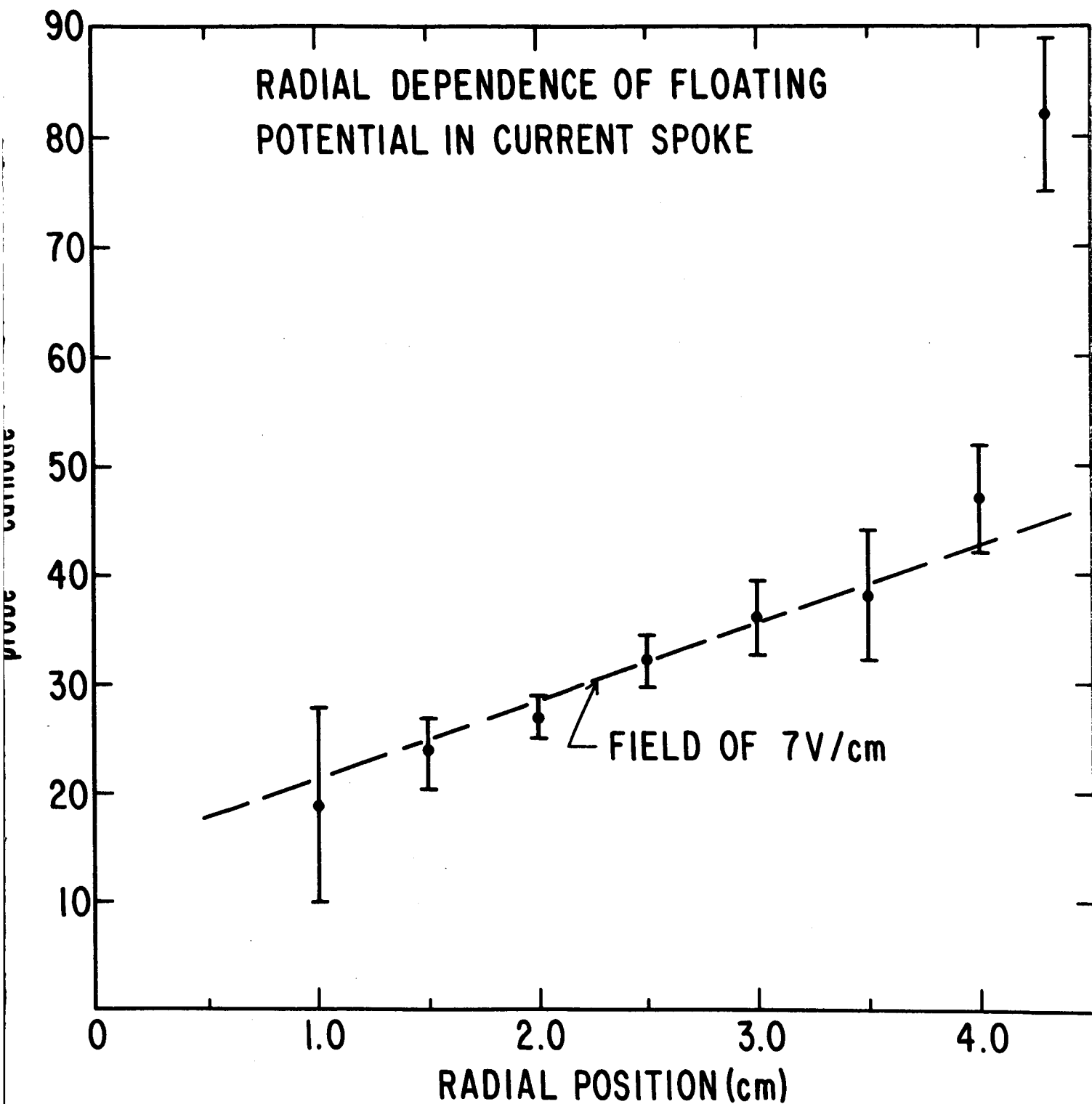


Fig. 8. Radial dependence of floating potential in spoke.

in arc current and bias field is shown in Figures 9 and 10. The anode drop for this measurement is assumed to be approximately equal to the difference between the floating potential of a probe 3mm from the anode and the anode potential.

There is an error inherent in this assumption due to the difference between the floating potential and the plasma space potential. Since the plasma seems to be moving azimuthally with the spoke, the order of magnitude of this error is easily estimated. Under standard conditions the azimuthal plasma streaming velocity near the anode is about

$$V_s \approx 10^6 \text{ cm/sec.}$$

which corresponds to a directed energy of

$$E_{\text{directed}} \approx 22 \text{ eV.}$$

At the floating potential the net current to the probe vanishes, i.e.

$$J_{\text{ion}} = J_{\text{electron}}$$

Neglecting the ion thermal motions and assuming that the electrons are Maxwellian we get

$$n_i e V_s = \frac{1}{4} n_e e \bar{c}_e e^{-eV_f/kT_e}$$

where V_f is the floating potential and \bar{c}_e is the mean electron thermal speed. Assuming quasi neutrality in the plasma and solving for V_f we get

$$V_f = \frac{kT_e}{e} \ln \left(\frac{\bar{c}_e}{4V_s} \right)$$

The logarithm factor is of the order of 2.7 in this case so that the resulting error is roughly 3 times the electron temperature in eV. The data can be corrected when the electron temperature is determined.

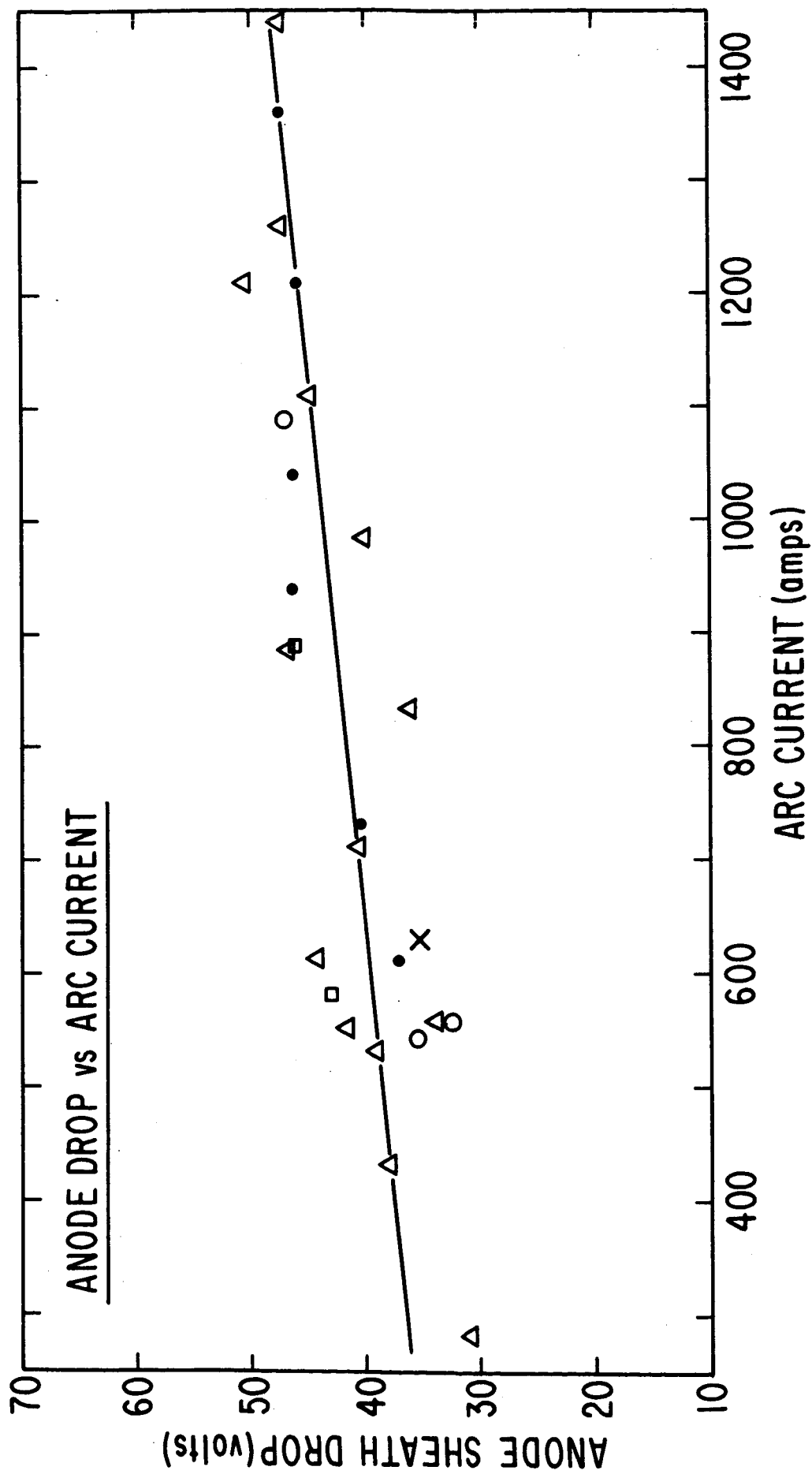


Fig. 9. Anode drop as a function of arc current.

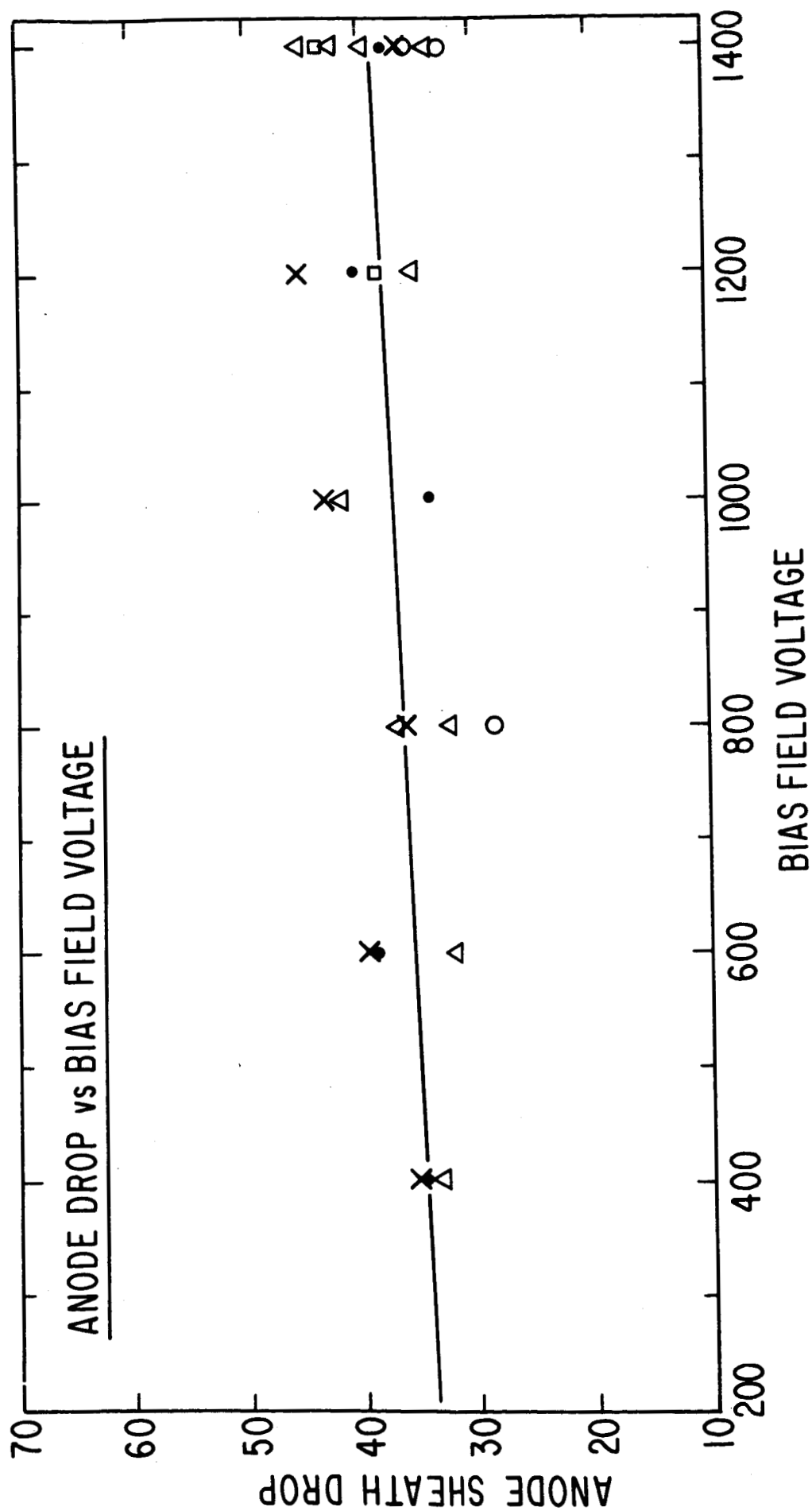


Fig. 10. Anode drop as a function of bias field.

Preliminary spectroscopic observations indicate that the electron temperature is less than 3 eV; therefore, the correction to the anode drop is probably less than 10 volts.

6. Biased probe measurements

The interpretation of Langmuir probe data in a magnetic field is very complicated. However, under standard conditions the ion gyro radius is larger than the Debye length and probe dimensions, therefore the effects of the magnetic field on the ions collected by the probe can be neglected. If now the probe is biased strongly negative with respect to the floating potential (and therefore also with respect to the plasma space potential) the plasma electrons are repelled and the probe collects ion saturation current.

Since the Debye length is very small and the mean free path of neutral atoms is large compared to a characteristic probe dimension, it is possible to write expressions for the ion saturation current density.

If the plasma streaming velocity relative to the probe is small compared to the mean ion thermal velocity

$$j_{\text{sat.}} = \alpha n e \left(\frac{k T_e}{m_i} \right)^{1/2}$$

where theories give α values from 0.4 to 1.0.

If the plasma streaming velocity is large compared to the ion thermal speeds

$$j_{\text{sat.}} = n e V_s$$

where V_s is the streaming velocity relative to the probe. This dependence on the plasma streaming velocity has been used to detect plasma velocities and, in particular, to determine whether the current spoke corresponds to

actual plasma motion or an ionization wave that is propagating azimuthally. This has been done by putting a pair of plane electrodes on opposite sides of a probe and orienting them in the azimuthal direction with one electrode facing the oncoming current spoke. If the plasma is not streaming relative to the probe, the two electrodes should collect equal current densities given by the theory of Bohm. A difference in the magnitudes of the saturation currents implies that the plasma is streaming relative to the probe. Figure 11 is a plot of the ion saturation currents to the front and rear electrodes as functions of radius. The current density to the front electrode is approximately proportional to the radius. Since the azimuthal spoke velocity is also proportional to the radius, the data seems to indicate that the plasma is moving with the current spoke.

A tacit assumption made in the preceding considerations is that the plasma density does not vary with radius. While this has not yet been firmly established, it seems very probable because of the lack of any radial dependence in both the observed radiation intensities and the ion saturation current to the rear electrode (Figure 11).

If the plasma is rotating with the spoke, the centrifugal force should accelerate the plasma radially causing it to be spun out to the anode. The biased probe was oriented radially, with one electrode facing the cathode, in order to detect radial plasma streaming velocities. Figure 12 shows the time dependence of the ion saturation currents to the inside and outside electrodes.

An internal spoke structure seems to be evident from the data in Figure 12. At the leading edge of the spoke the net radial plasma velocity is directed outward, while the plasma in the trailing edge of the spoke seems to be moving inward. The inward plasma motion seems to be correlated with the arc current density.

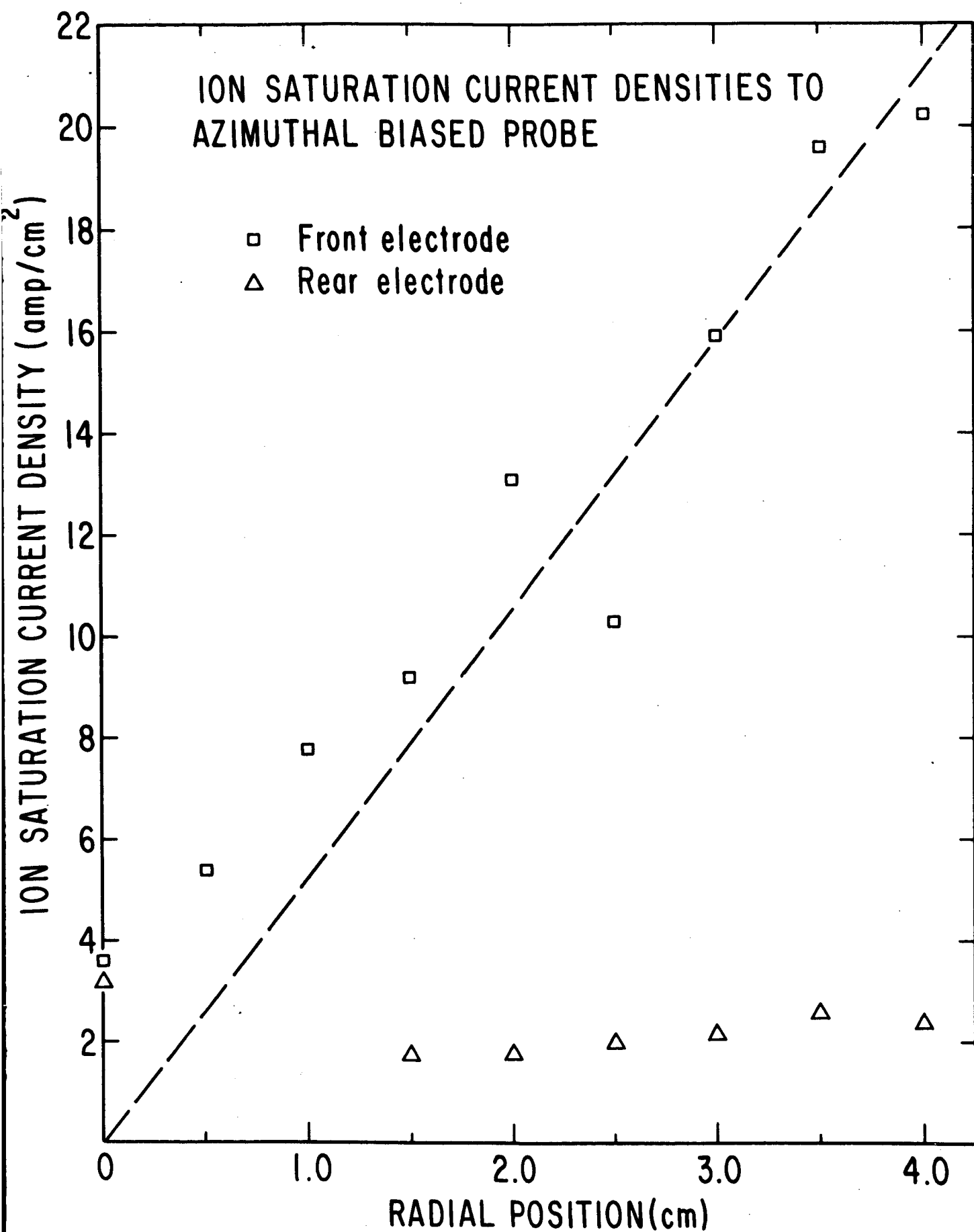


Fig. 11. Ion saturation current densities collected by azimuthal biased probe as a function of radius.

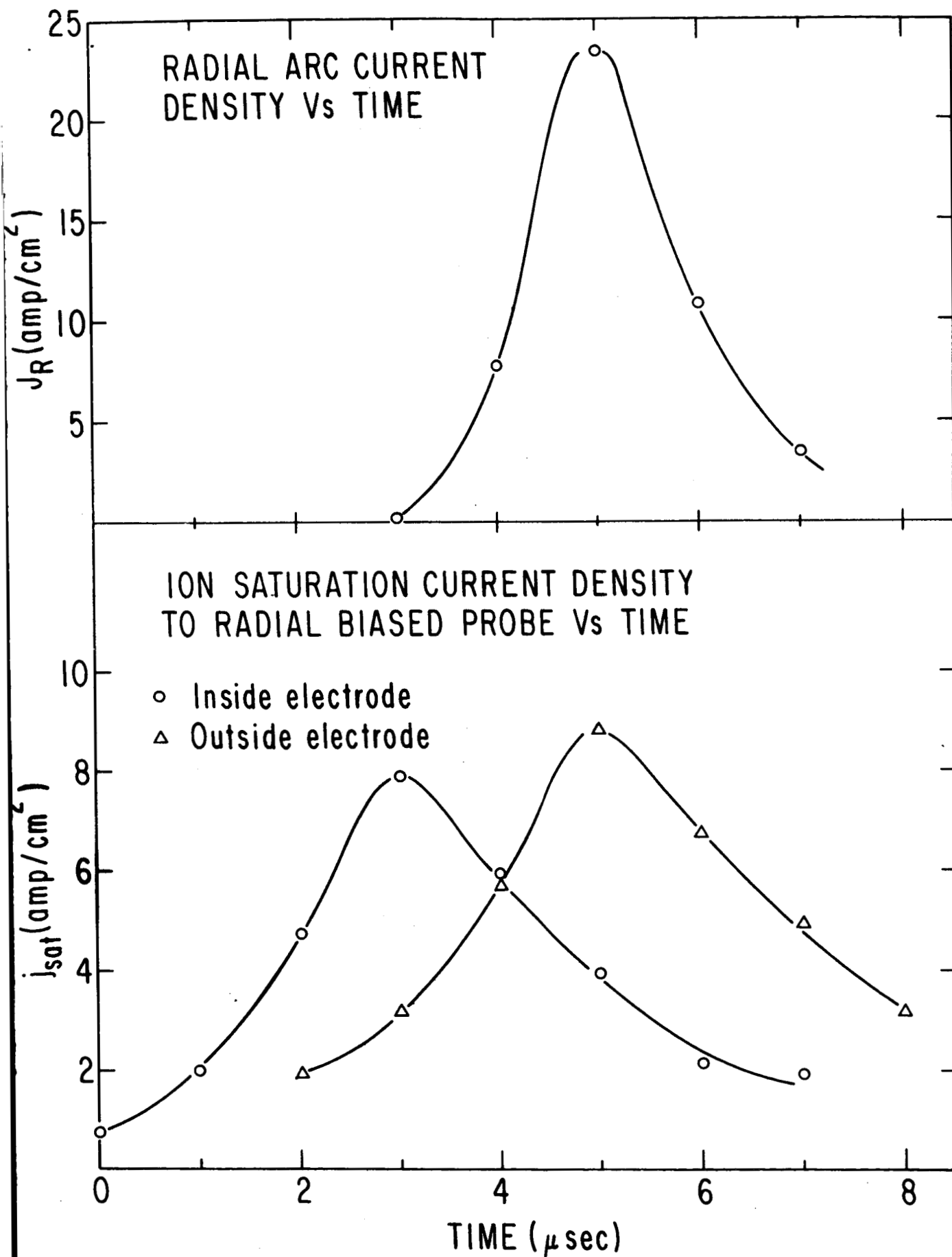


Fig. 12. Ion saturation current collected by radial biased probe and the radial arc current density measured with Rogowski coil as functions of time.

An attempt is now underway to construct an MHD model of the plasma spoke. A computer code is being developed for this purpose.

7. Beam analysis

Further testing of the device described in the last report indicated that the observed energy spectrum had been severely distorted by charge exchange processes within the analyzer.

In order to reduce the charge exchange to an acceptable level, a more compact analyzer is now under construction. A plasma shutter has been incorporated into the design, so that both the energy and velocity distributions can be determined. It will then be possible to establish the relative contributions of the different stages of ionization.

8. Summary

More detailed measurements of spatial distributions of current and potential have been made possible through the development of improved diagnostics.

The development of the photomultiplier telescope permits spatial resolution of the visible radiation emitted by the plasma. The source of the radiation seems to have roughly the same spatial structure as the current in the arc.

Biased probe measurements indicate that the plasma is moving azimuthally with the spoke and that the spoke exhibits some internal structure. The development of an MHD model of the spoke is in progress.

Figure Captions

- Fig. 1. Spoke rotation frequency vs. IB.
- Fig. 2. Equal current density contours and current streamlines of center of spoke.
- Fig. 3. θ Distribution of current.
- Fig. 4. ΔB_z at a radius slightly less than that of anode sheath.
- Fig. 5. Photomultiplier telescope output.
- Fig. 6. Radial and azimuthal electric fields in the spoke.
- Fig. 7. Contours of equal floating potential.
- Fig. 8. Radial dependence of floating potential in spoke.
- Fig. 9. Anode drop as a function of arc current.
- Fig. 10. Anode drop as a function of bias field.
- Fig. 11. Ion saturation current densities collected by azimuthal biased probe as a function of radius.
- Fig. 12. Ion saturation current collected by radial biased probe and the radial arc current density measured with Rogowski coil as functions of time.